AD-008 660

A SENSITIVITY STUDY OF THERMAL RADIATION FLUENCE FROM A NUCLEAR AIR BURST

Joel D. Jonnson

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

March 1975

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER GNE/PH/75-7	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER AD-A008 660	
4. TITLE (and Subtitle) A SENSITIVITY STUDY OF THERMAL RADIATION FLUENCE FROM A NUCLEAR AIR BURST	5. TYPE OF REPORT & PERIOD COVERED MS THESIS
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Joel D. Johnson Captain USAF	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, OHIO 45433	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Weapons Laboratory (SA) Kirtland AFB, New Mexico 87115	12. REPORT DATE March 1975
	13. NUMBER OF PAGES 70
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for Public Release
IAW AFR 190-17

JERRY C. HIX, Captain, USAF
Director of Information
Air Force Institute of Technology

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thermal Radiation
Thermal Fluence
Nuclear Air Burst
Sensitivity of Thermal Fluence
Atmospheric Cross Sections

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A sensitivity study was made on four variables which must be specified to compute the thermal radiation fluence in the atmosphere from a nuclear burst. These parameters are: the choice and number of energy bands used to specify the atmospheric attenuation coefficients, the relative importance of scatter, the significance of source (fireball) temperature and the importance of height of burst. These parameters were examined by computing

20.
the thermal fluence as the variables were changed, one by one. The number of groups was varied from four to sixteen. The source temperature was examined over a range from 3500°K to 8500°K and burst altitudes to 30 km were considered. The importance of scatter was evaluated by computing the fluence first with an attenuation factor composed only of absorption and then with an attenuation which was the sum of absorption and scatter. All of these calculations were carried out with a FORTRAN IV computer code prepared by the author. The code is described here for possible future use. The results of the parametric variation indicated that: one needs 14 energy bands in the infrared region, scatter is important in computing fluence at altitudes below five km, the computed fluence is relatively insensitive to source temperature over the range considered and that burst height charges can be modeled by changing source temperature.

GNE/PH/75-7

A SENSITIVITY STUDY OF THERMAL RADIATION FLUENCE FROM A NUCLEAR AIR BURST

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

Joel D. Johnson, BS
Captain USAF

Graduate Nuclear Engineering

March 1975

Approved for public release; distribution unlimited

i4

Preface

I wish to thank Mr. Alfred Sharp and Major Harold Meisterling of the Air Force Weapons Laboratory at Kirtland AFB for their assistance in providing information on thermal effects. I gratefully acknowledge the assistance of Majors Carl Case and Kenneth Jungling of the AFIT Physics Department in locating information on atmospheric transmittance. Dr. Charles J. Bridgman, my thesis advisor at AFIT, provided helpful guidance and suggestions throughout the research period. I wish to acknowledge my indebtedness to my wife, Cathy, for her assistance in the preparation of this thesis and to my daughter, Lisa, for her morale-boosting sunny personality.

Joel D. Johnson
Captain, USAF

Contents

List of Figures

List of Tables

Abstract

A sensitivity study was made on four variables which must be specified to compute the thermal radiation fluence in the atmosphere from a nuclear burst. These parameters are: the choice and number of energy bands used to specify the atmospheric attenuation coefficients, the relative importance of scatter, the significance of source (fireball) temperature and the importance of height of burst. These parameters were examined by computing the thermal fluence as the variables were changed, one by one. The number of groups was varied from four to sixteen. The source temperature was examined over a range from 3500°K to 8500°K and burst altitudes to 30 km were considered. The importance of scatter was evaluated by computing the fluence first with an attenuation factor composed only of absorption and then with an attenuation which was the sum of absorption and scatter. All of these calculations were carried out with a FORTRAN IV computer code prepared by the author. The code is described here for possible future use. The results of the parametric variation indicated that: one needs 14 energy bands in the infrared region, scatter is important in computing fluence at altitudes below five km, the computed fluence is relatively insensitive to source temperature over the range considered and that burst height changes can be modeled by changing source temperature.

A SENSITIVITY STUDY OF THERMAL RADIATION FLUENCE FROM A NUCLEAR AIR BURST

I. Introduction

Calculations of the effects of nuclear weapons are important in predicting the survivability/vulnerability of Air Force systems. Thermal radiation, one of the major effects generated by the fireball of a nuclear explosion, contributes approximately 30 to 40 percent of the total weapon yield from an air burst (Ref 2:7).

The objective of this thesis is to present a sensitivity study of the thermal fluence from a nuclear air burst incident on a receiver in the atmosphere. A nuclear air burst is defined as a burst at an altitude of less than 100,000 ft, or about 30 km. For the discussion and examples to follow, both burst and receiver are equal to or less than 30 km. Virgin radiation is that fraction of the thermal radiation which is unscattered and not absorbed by the atmosphere. When calculating the virgin fluence, all scatter and absorption results in a loss of radiation to the receiver. Fluence is the time integrated energy flux and is measured in units of energy per unit area.

Chapter II of this report presents a short overview of the theory of thermal radiation from an air burst. Here, the source of the radiation is presented along with a transmission model based on diffusion theory, in order to develop a physical basis for the calculation of fluence. The energy range of the thermal photons and the possible mechanisms of photon interaction with the atmosphere are examined. The degree of photon interaction with the atmosphere is measured by the photon cross sections determined in Chapter III. Atmospheric models of the earth's atmosphere are compared and cross sections are determined by the use of transmittance data developed by R. A. McClatchey of the Air Force Cambridge Research Laboratory. Chapter IV presents a series of sensitivity studies made by calculating thermal fluence from an air burst. The parameters studied are: the choice and number of energy bands used to specify the atmospheric attenuation coefficients, the relative importance of scatter, the significance of source (fireball) temperature, and the importance of height of burst.

All the cross section determinations and sensitivity studies are combined in the development of a thermal code in Chapter V. The results of computer problems with 200-kiloton bursts summarize the conclusions of the sensitivity study. The code is developed using basic FORTRAN IV programming language which can be followed by a student with only a basic understanding of FORTRAN.

II. Theory of Thermal Radiation Phenomenon

Source

The source of thermal radiation in a nuclear explosion is the fireball. In an air burst, the emission of thermal radiation is in two pulses which correspond to the rise and fall of the apparent surface temperature of the fireball. The two pulses are illustrated in Figure 1.

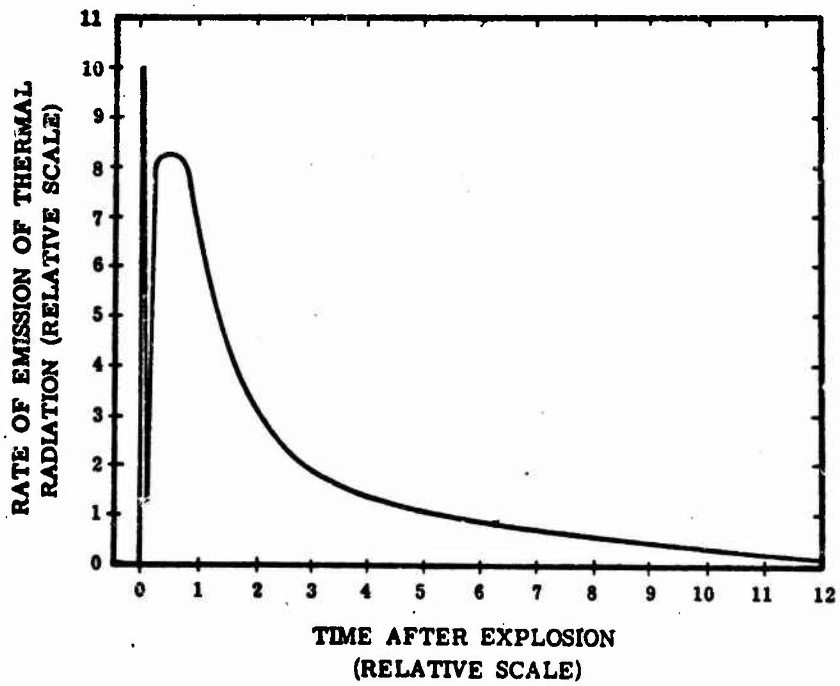

Fig. 1. Emission of Thermal Radiation in Two Pulses in an Air Burst (Ref 6:45).

In the first pulse, there is only about one percent of the thermal radiation because of its short duration, which is about 0.1 second for a one-megaton explosion. The second pulse may last for several seconds and carries about 99 percent of the total thermal radiation (Ref 6:45). The first pulse is neglected in calculations of thermal radiation from an air burst.

The average surface temperature of the fireball for the second pulse is approximately $6000^{\circ}K$. The fireball acts much like the sun and can be approximated by a blackbody radiator, so a $6000^{\circ}K$ blackbody is often used as the source in a simple model of a nuclear air burst. The nuclear air burst spectrum will vary from the $6000^{\circ}K$ blackbody mostly in the ultraviolet region (Ref 9).

Transmission

The theory of transmission of thermal radiation can be developed from the diffusion equation. Assume a point source with a homogeneous atmosphere and all scatter as removal. Because of the absence of scatter, the thermal radiation acts like streaming particles. Therefore the fluence, $F(r)$, is equal to the net current and is a function of the distance from the source. Under these conditions, the diffusion equation can be written

$$\frac{dF(r)}{dr} + \frac{2}{r}F(r) + \mu F(r) = 0 \tag{1}$$

where r is the distance from the source and μ is the total cross section (per unit length), which is defined as the absorption plus scatter cross sections. Rearranging equation (1) and integrating from the radius of the fireball, r_{fb}, to the receiver, R, gives

$$\int_{r_{fb}}^{R} \frac{dF(r)}{F(r)} = -\int_{r_{fb}}^{R} \frac{2}{r} dr - \mu \int_{r_{fb}}^{R} dr \tag{2}$$

which is

$$F(R) = \frac{r_{fb}^2 F(r_{fb})}{R^2} \exp\left(-\mu(R - r_{fb})\right) \tag{3}$$

Applying boundary conditions

$$\lim_{r \to r_{fb}} \left(4\pi r^2 F(r)\right) = Y \tag{4}$$

where Y is the thermal yield (energy)

$$F(r_{fb}) = \frac{Y}{4\pi r_{fb}^2} \tag{5}$$

and substituting Equation (5) into Equation (3) yields

$$F(R) = \frac{Y}{4\pi R^2} \exp(-\mu R) \tag{6}$$

where the fireball is assumed the point source such that r_{fb} is zero. The expression $\exp(-\mu R)$ is the atmospheric transmittance, T. Atmospheric transmittance, through the cross section term μ, is a function of many variables; wavelength of radiation, path length of transmission, atmospheric gases, pressure, temperature, amounts of aerosols and the size distribution of the aerosols (Ref 4:81). If a point source is assumed and effects of the atmosphere are ignored, the thermal fluence at the receiver could be calculated by

$$F = \frac{Y}{4\pi R^2} \tag{7}$$

where F is the thermal fluence (energy per unit area), and Y is the thermal yield (energy), and R is the path length between burst and receiver (length). The only attenuation of thermal radiation would be spherical divergence given by $4\pi R^2$.

Spectrum from an Air Burst

The range of thermal photon energies from the source is assumed to correspond to a 6000°K Planckian distribution. Using RAND Planckian tables (Ref 5), the range from 0.2 to 4.0 microns contained approximately 99 percent of the thermal radiation emitted. The thermal spectrum of 0.2 to 4.0 microns can be divided into three broad bands; ultraviolet, visible and infrared. Figure 2 gives the band limits in terms of wavelength, frequency and energy.

In terms of percent of thermal yield in each band, approximately 13.8 percent is in the ultraviolet, 37.5 percent in the visible and 47.6 percent in the infrared.

Photon Interactions with the Atmosphere

The total cross section, μ, determines the degree of interaction between the thermal radiation and the atmosphere. The atmosphere consists of molecules and aerosols. Molecules are very small, on the order of 10^{-6} to 10^{-8} microns.

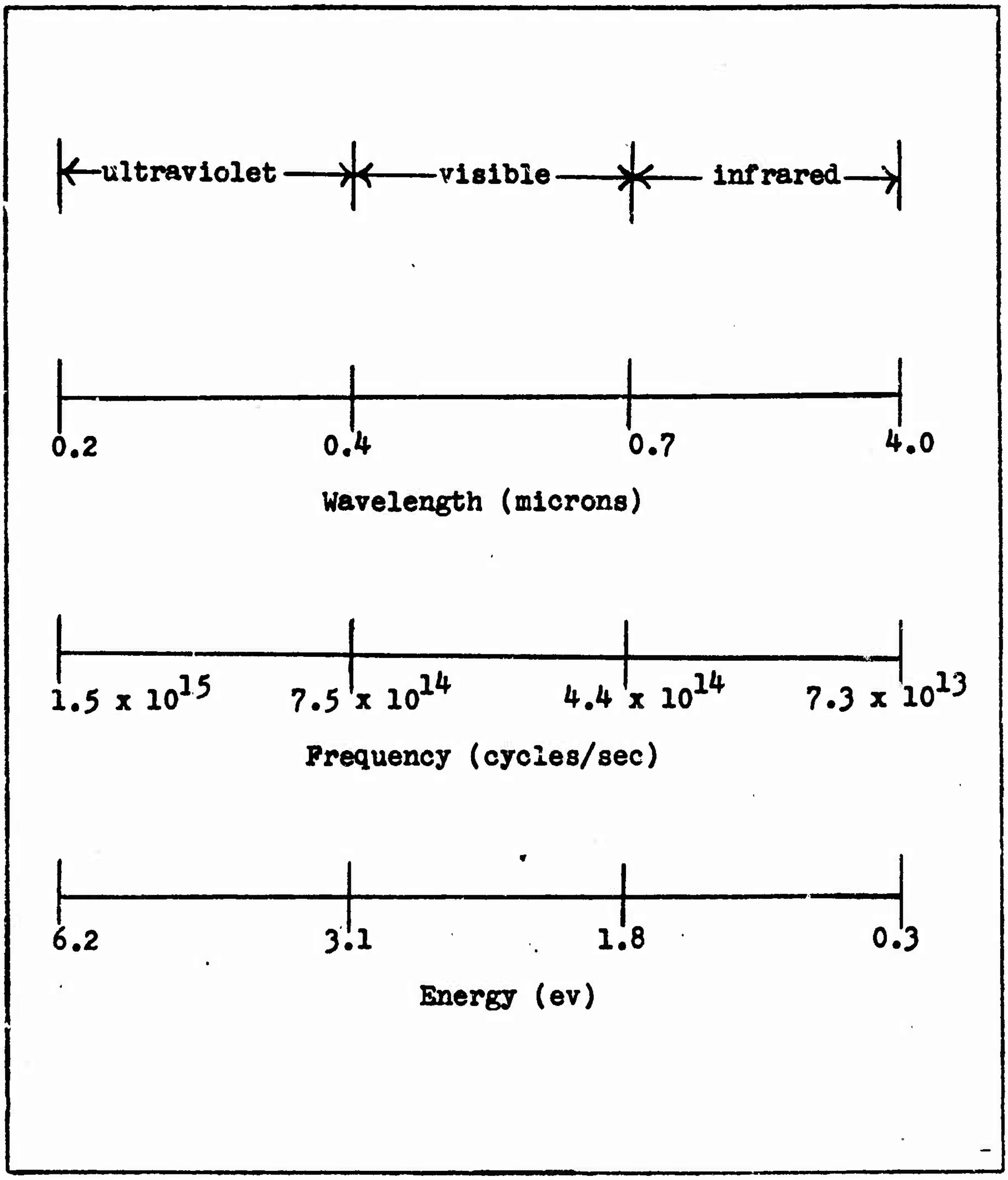

Fig. 2. Broad Band Structure of Thermal Spectrum in an Air Burst.

Aerosols are dispersed solid particles or liquid droplets in a gaseous medium, in this case the atmosphere, and they range in size on the order of 0.1 to 10 microns. There are two mechanisms of interaction; absorption and scatter.

Absorption. The absorption cross sections for molecules are a function of not only the amount of absorbing gas, but also the local temperature and pressure of the gas. The variation of the molecular absorption with wavelength is very complicated, being a highly variable function of wavelength (Ref 8:11).

The absorption cross sections for aerosols depend on the number density and size distribution of aerosols as well as the complex index of refraction. The amount of absorption can be derived theoretically for spherical particles by use of Mie theory. The absorption cross section due to aerosol distributions is a smooth function of wavelength.

Scatter. The scatter cross sections for molecules depend only on the number density of molecules in the radiation path. The wavelength dependence of molecular scattering is very nearly proportional to the inverse fourth power of wavelength. All atmospheric molecules scatter radiation. If the atmospheric molecules are assumed to be spherical and small relative to the wavelength of the incident radiation, the phenomenon is called Rayleigh scattering.

The scatter cross section for aerosols depends on the number density and size distribution of aerosols. The amount of scatter can be derived by use of Mie theory and is a smooth function of wavelength.

The determination of atmospheric attenuation is reduced to a calculation of the attenuation due to aerosol and molecular cross sections. The total aerosol cross section is the sum of the scatter and absorption:

$$\mu_a = \alpha_a + \beta_a \tag{8}$$

where α_a is the aerosol absorption cross section (per unit length) and β_a is the aerosol scattering cross section (per unit length). Likewise, the molecular cross section is the sum of the molecular scattering and absorption:

$$\mu_m = \alpha_m + \beta_m \tag{9}$$

where μ_m is the molecular absorption cross section (per unit length) and β_m is the molecular scattering cross section (per unit length).

The total cross section, μ, is the sum of the molecular and aerosol cross sections and is often called an attenuation cross section.

III. Determination of Photon Cross Sections

Atmospheric Models

The atmospheric models considered to determine cross sections used in the calculation of virgin thermal fluence were models compiled by Air Force Cambridge Laboratory (AFCRL)(Ref 8). Six model atmospheres are defined for temperature, pressure and absorbing gas concentrations. In addition to these atmospheres, two aerosol models have been defined and are available for use with the six models.

Five of the model atmospheres compiled by AFCRL represent different climatological conditions that are typical for seasonal conditions and geographical locations, namely, Tropical, Midlatitude Summer, Midlatitude Winter, Subarctic Summer and Subarctic Winter. The sixth, the U. S. Standard Atmosphere, 1962, was also compiled, with an appropriate water vapor and ozone distribution. The U. S. Standard Atmosphere provides a single appropriate atmospheric model for comparison within the Atmospheric Physics community.

The two aerosol models compiled by AFCRL describe a "clear" and "hazy" atmosphere corresponding to a visibility of 23 and 5 km respectively at ground level. The aerosol size distribution function for both models is the same at all altitudes. The aerosols considered vary in size from 0.02 to 10 microns. The "hazy" model is identical to the "clear" model for altitudes equal to or greater than five km.

For altitudes less than five km, the total number of aerosol particles increases exponentially to reach a value at ground level corresponding to a ground visibility of approximately five km.

For the purpose of this study, the U. S. Standard Atmosphere and the Tropical Atmospheres coupled with the "clear" and "hazy" aerosol distributions were used to determine cross sections for the calculation of virgin fluence. The U. S. Standard Atmosphere was chosen to represent a "dry" atmosphere and the Tropical Atmosphere a "wet" atmosphere. Tables I and II give the concentrations and meteorological condition as they vary with height for the atmospheres chosen.

Transmission Data

Cross sections were determined by the use of transmission data compiled by McClatchey of AFCRL (Ref 8). The U. S. Standard and Tropical Atmospheres, along with the aerosol models, were used to determine specific amounts of a constituent at a particular altitude. The amounts were converted into scaling factors for a one-km path length by multiplying each amount by one km. The scaling factors were used for the determination of cross sections from transmission charts. Numerical values for cross sections were computed for one-km intervals from 0 through 30 km. The aerosol attenuation cross sections are assumed identical for all geographical

Table I

U. S. Standard Atmosphere (Ref 8:94)

U.S. STANDARD ATMOSPHERE, 1962					
Ht. (km)	Pressure (mb)	Temp. (°K)	Density (g/m³)	Water Vapor (g/m³)	Ozone (g/m³)
0	1.013E+03	288.1	1.225E+03	5.9E+00	5.4E-05
1	8.986E+02	281.6	1.111E+03	4.2E+00	5.4E-05
2	7.950E+02	275.1	1.007E+03	2.9E+00	5.4E-05
3	7.012E+02	268.7	9.093E+02	1.8E+00	5.0E-05
4	6.166E+02	262.2	8.193E+02	1.1E+00	4.6E-05
5	5.405E+02	255.7	7.364E+02	6.4E-01	4.5E-05
6	4.722E+02	249.2	6.601E+02	3.8E-01	4.5E-05
7	4.111E+02	242.7	5.900E+02	2.1E-01	4.8E-05
8	3.565E+02	236.2	5.258E+02	1.2E-01	5.2E-05
9	3.080E+02	229.7	4.671E+02	4.6E-02	7.1E-05
10	2.650E+02	223.2	4.135E+02	1.8E-02	9.0E-05
11	2.270E+02	216.8	3.648E+02	8.2E-03	1.3E-04
12	1.940E+02	216.6	3.119E+02	3.7E-03	1.6E-04
13	1.658E+02	216.6	2.666E+02	1.8E-03	1.7E-04
14	1.417E+02	216.6	2.279E+02	8.4E-04	1.9E-04
15	1.211E+02	216.6	1.948E+02	7.2E-04	2.1E-04
16	1.035E+02	216.6	1.665E+02	6.1E-04	2.3E-04
17	8.850E+01	216.6	1.423E+02	5.2E-04	2.8E-04
18	7.565E+01	216.6	1.216E+02	4.4E-04	3.2E-04
19	6.467E+01	216.6	1.040E+02	4.4E-04	3.5E-04
20	5.529E+01	216.6	8.891E+01	4.4E-04	3.8E-04
21	4.729E+01	217.6	7.572E+01	4.8E-04	3.8E-04
22	4.047E+01	218.6	6.451E+01	5.2E-04	3.9E-04
23	3.467E+01	219.6	5.500E+01	5.7E-04	3.8E-04
24	2.972E+01	220.6	4.694E+01	6.1E-04	3.6E-04
25	2.549E+01	221.6	4.008E+01	6.6E-04	3.4E-04
30	1.197E+01	226.5	1.841E+01	3.8E-04	2.0E-04
35	5.746E+00	236.5	8.463E+00	1.6E-04	1.1E-04
40	2.871E+00	250.4	3.996E+00	6.7E-05	4.9E-05
45	1.491E+00	264.2	1.966E+00	3.2E-05	1.7E-05
50	7.978E-01	270.6	1.027E+00	1.3E-05	4.0E-06
70	5.520E-02	219.7	8.754E-02	1.5E-07	8.6E-08
100	3.008E-04	210.0	4.989E-04	1.0E-09	4.3E-11

Table II

Tropical Atmosphere (Ref 8:3)

TROPICAL					
Ht. (km)	Pressure (mb)	Temp. (°K)	Density (g/m^3)	Water Vapor (g/m^3)	Ozone (g/m^3)
0	1.013E+03	300.0	1.167E+03	1.9E+01	5.6E-05
1	9.040E+02	294.0	1.064E+03	1.3E+01	5.6E-05
2	8.050E+02	288.0	9.689E+02	9.3E+00	5.4E-05
3	7.150E+02	284.0	8.756E+02	4.7E+00	5.1E-05
4	6.330E+02	277.0	7.951E+02	2.2E+00	4.7E-05
5	5.590E+02	270.0	7.199E+02	1.5E+00	4.5E-05
6	4.920E+02	264.0	6.501E+02	8.5E-01	4.3E-05
7	4.320E+02	257.0	5.853E+02	4.7E-01	4.1E-05
8	3.780E+02	250.0	5.258E+02	2.5E-01	3.9E-05
9	3.290E+02	244.0	4.708E+02	1.2E-01	3.9E-05
10	2.860E+02	237.0	4.202E+02	5.0E-02	3.9E-05
11	2.470E+02	230.0	3.740E+02	1.7E-02	4.1E-05
12	2.130E+02	224.0	3.316E+02	6.0E-03	4.3E-05
13	1.820E+02	217.0	2.929E+02	1.8E-03	4.5E-05
14	1.560E+02	210.0	2.578E+02	1.0E-03	4.5E-05
15	1.320E+02	204.0	2.260E+02	7.6E-04	4.7E-05
16	1.110E+02	197.0	1.972E+02	6.4E-04	4.7E-05
17	9.370E+01	195.0	1.676E+02	5.6E-04	6.9E-05
18	7.890E+01	199.0	1.382E+02	5.0E-04	9.0E-05
19	6.660E+01	203.0	1.145E+02	4.9E-04	1.4E-04
20	5.650E+01	207.0	9.515E+01	4.5E-04	1.9E-04
21	4.800E+01	211.0	7.938E+01	5.1E-04	2.4E-04
22	4.090E+01	215.0	6.645E+01	5.1E-04	2.8E-04
23	3.500E+01	217.0	5.618E+0[illegible]	5.4E-04	3.2E-04
24	3.000E+01	219.0	4.763E+01	6.0E-04	3.4E-04
25	2.570E+01	221.0	4.045E+01	6.7E-04	3.4E-04
30	1.220E+01	232.0	1.831E+01	3.6E-04	2.4E-04
35	6.000E+00	243.0	8.600E+00	1.1E-04	9.2E-05
40	3.050E+00	254.0	4.181E+00	4.3E-05	4.1E-05
45	1.590E+00	265.0	2.097E+00	1.9E-05	1.3E-05
50	8.540E-01	270.0	1.101E+00	6.3E-06	4.3E-06
70	5.790E-02	219.0	9.210E-02	1.4E-07	8.6E-08
100	3.000E-04	210.0	5.000E-04	1.0E-09	4.3E-11

and seasonal models.

The cross sections calculated are average cross sections over a given band width. The average cross sections are weighted by the Planckian distribution of photons given by the 6000°K average temperature source. The band widths were determined by sensitivity studies which will be explained in Chapter IV. Average cross sections for aerosol and molecule absorption and scatter are summed to determine an average total cross section (attenuation) for a given altitude.

The transmission charts used to calculate the aerosol and molecule cross sections are all similar to Figure 3. The variation of transmittance with respect to wavelength can be determined by use of a vertical transmittance scale associated with a set of scaling factors for the absorber amount. In order to use the charts efficiently, it is necessary to trace the transmittance scale and associated factors on to some transparent paper. Thus by displacing the transmittance scale horizontally according to wavelength and vertically according to the appropriate equivalent sea level quantity, one can construct a transmittance spectrum for any band interval. The transmittance spectrum can be converted to an average cross section for a band by weighting the transmission spectrum with a Planckian distribution representative of the photon source.

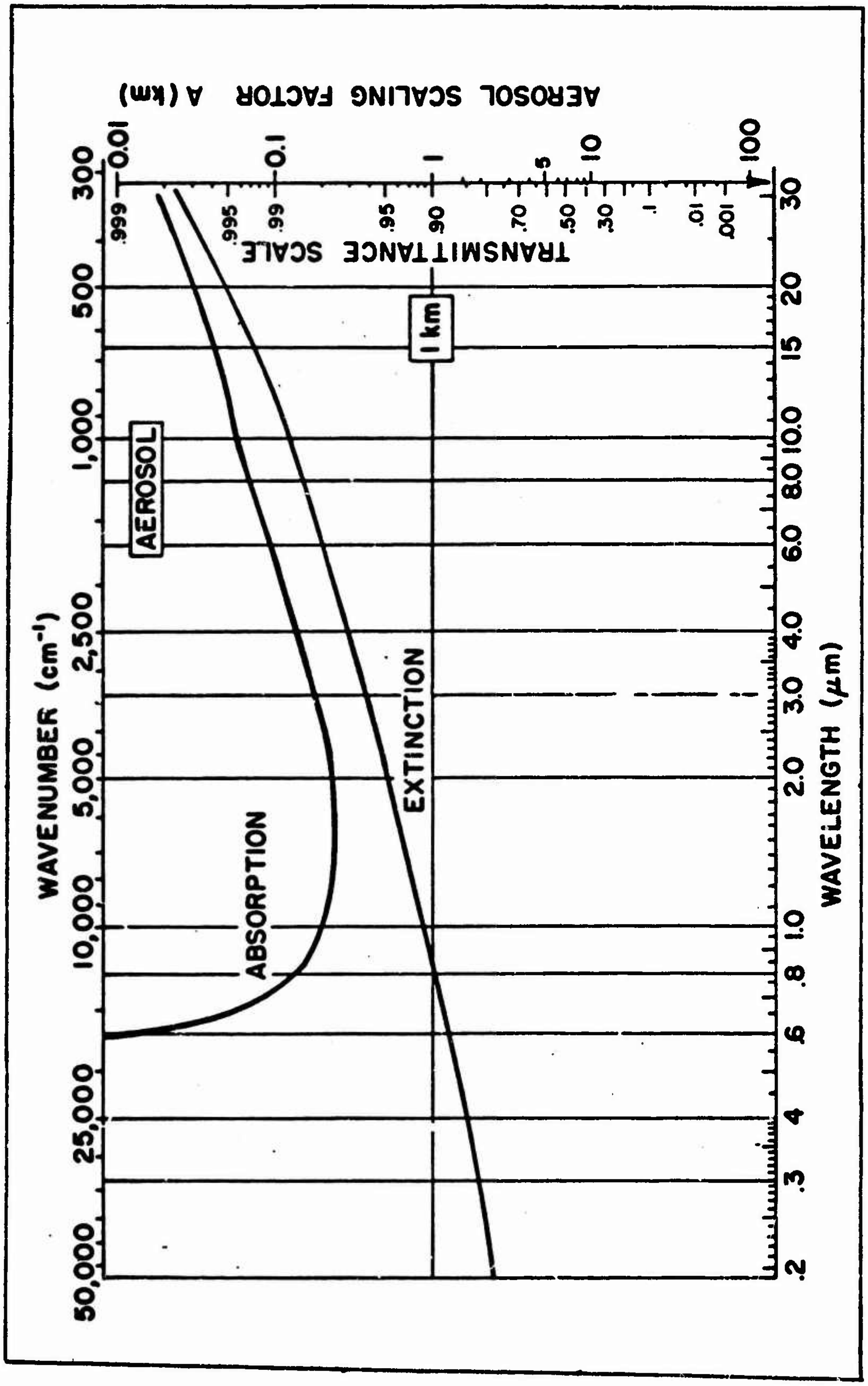

Figure 3. Prediction Chart for Aerosol Transmittance (Scattering and Absorption) (Ref 8:68)

The cross sections are determined from the transmittance, which is

$$T = \exp(-\mu R) \qquad (10)$$

Solving (10) for μ yields

$$\mu = -\frac{\ln T}{R} \qquad (11)$$

where R is equal to one km and μ is the cross section in units km^{-1}.

The equivalent sea level absorber amounts for a given atmosphere or aerosol distribution are given in charts like the one in Figure 4. The a_h (aerosol) on the vertical scale of Figure 4 is the ratio of number density of aerosols at a particular altitude to the number density of aerosols at sea level for a visibility of 23 km (Ref 8:34). Using Figure 4, a_h at an altitude of zero km for a visibility of 23 km is one. The aerosol scaling factor, A (km), for a one-km path is therefore one km. If the transmittance scale of Figure 3 is placed on the chart so that the scaling factor, one km, rests on the datum line (as shown in Figure 3), then the transmittance can be read off as a function of wavelength for aerosol absorption or extinction (absorption plus scatter). The chart is moved horizontally until the transmittance scale is positioned directly above the required wavelength and read off the transmittance where the scale crosses the curve. For example, in Figure 3

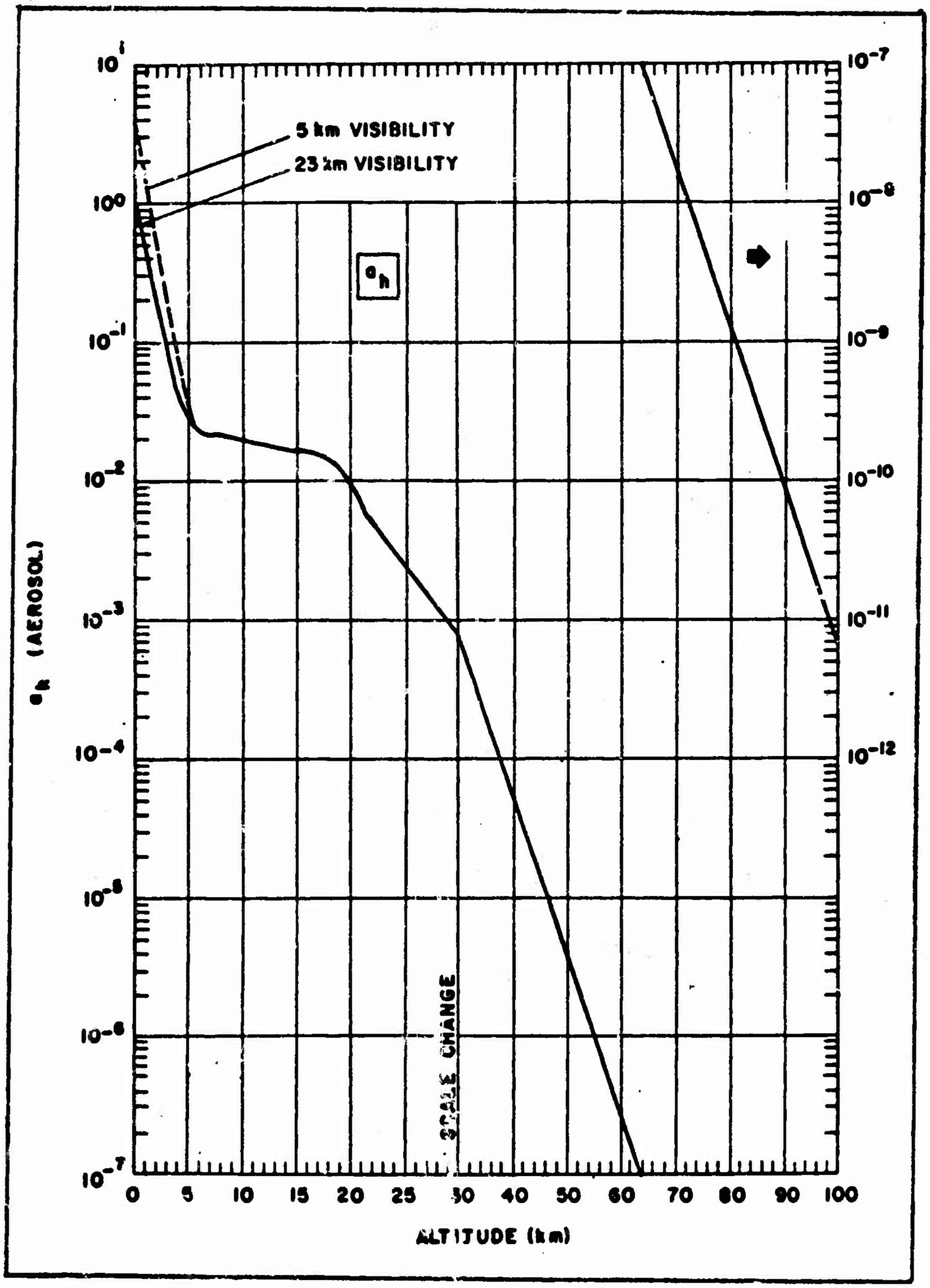

Figure 4. Equivalent Sea Level Path Length for Aerosol Extinction as a Function of Altitude for Horizontal Atmospheric Paths (Ref 8:57)

the scale is set to the right of 30 microns and the transmittance is approximately 0.998. If the transmittance is required for a different aerosol scaling factor, for example, A = 0.01 km for a 1-km path at a 20-km altitude, the transmittance scale is displaced vertically until the scaling factor 0.01 is coincident with the datum line. The scale is then moved horizontally to the required wavelength and read off the transmittance. The one-km transmittance can be converted to cross sections, per kilometer, and averaged over the appropriate band interval.

Using charts for aerosol and molecule absorption and scatter, average cross sections can be determined for every kilometer from 0 through 30 km. The sum of the individual scatter and absorption cross sections will determine the total cross section defined in Chapter II. These cross sections will be average cross sections over a given band.

The average total cross sections determined will consider aerosol absorption from 0.6 to 4.0 microns and aerosol scatter from 0.2 to 4.0 microns. The only atmospheric molecule considered in this report from 0.2 to 0.7 microns is ozone. Therefore, all molecular absorption in wavelengths less than 0.7 microns will be determined from ozone amounts. Molecule absorption for wavelength greater than 0.7 microns will consider water vapor and uniformly mixed gases (CO_2, N_2O, CO, CH_4, and O_2) amounts.

The overall accuracy in cross sections is limited by graphical techniques. McClatchey points out that the accuracy of the transmittance which this technique provides is better than 10 percent. The curves presented in the transmittance charts tend to overestimate the transmittance for very long paths and underestimate the transmittance for very short paths (Ref 8:37).

The average total cross sections for given band intervals at one-km increments from 0 through 30 km are given in Appendix B.

IV. Sensitivity of Thermal Fluence From an Air Burst

Before developing a computer code to calculate the virgin fluence from an air burst, several sensitivity studies are accomplished to determine the significance of the different parameters and assumptions considered. The goal of the sensitivity studies is to determine a reliable method for calculating thermal fluence. The choice and number of energy bands used to specify the atmospheric attenuation coefficients, the relative importance of scatter, the significance of source (fireball) temperature, and the importance of height of burst will be considered.

Number and Choice of Energy Bands

From an examination of the range of thermal photon energies, the grouping of the photon energies into ultraviolet, visible and infrared bands is the most natural way to group the energy distribution. The infrared band is divided into band numbers I (0.7 - 1.2 microns) and II (1.2 - 4.0 microns) to separate the "near" and "far" infrared respectively. Average total cross sections for each band are determined by methods explained in Chapter III. This band grouping is defined as the "broad" band model since each band spans a broad wavelength interval.

An examination of McClatchey's transmittance charts, for example Figure 3, indicates that in the ultraviolet and visible bands the cross sections are slowly varying and treatment as a single broad group should be reasonably accurate, however in the infrared region large discontinuities exist in the cross section variations with photon wavelength within these broad bands. These atmospheric "windows" (regions with no attenuation) for water vapor absorption cross sections are averaged over when the infrared region is divided into bands. A "fine" band infrared model is determined by dividing the infrared band, 0.4 - 4.0 microns, into 14 separate bands. The divisions between the bands are determined by a visual inspection of the transmittance chart for water vapor absorption, as can be seen in Figure 5. Divisions are chosen at wavelengths where large discontinuities are obvious from a visual inspection of the transmittance chart. The band numbers and wavelength limits (in microns) are given in Table 5 in Appendix C. To compare the "broad" and "fine" band models, a series of virgin thermal fluence calculations were made.

The virgin thermal fluence is calculated using equation (6) on page 5 of Chapter II. These calculations are based on three considerations. The first is a thermal yield of 100 kilotons. Secondly, a 6000^{o}K blackbody source is used for the distribution of energies by band. Finally, the average cross sections consider only the absorption due

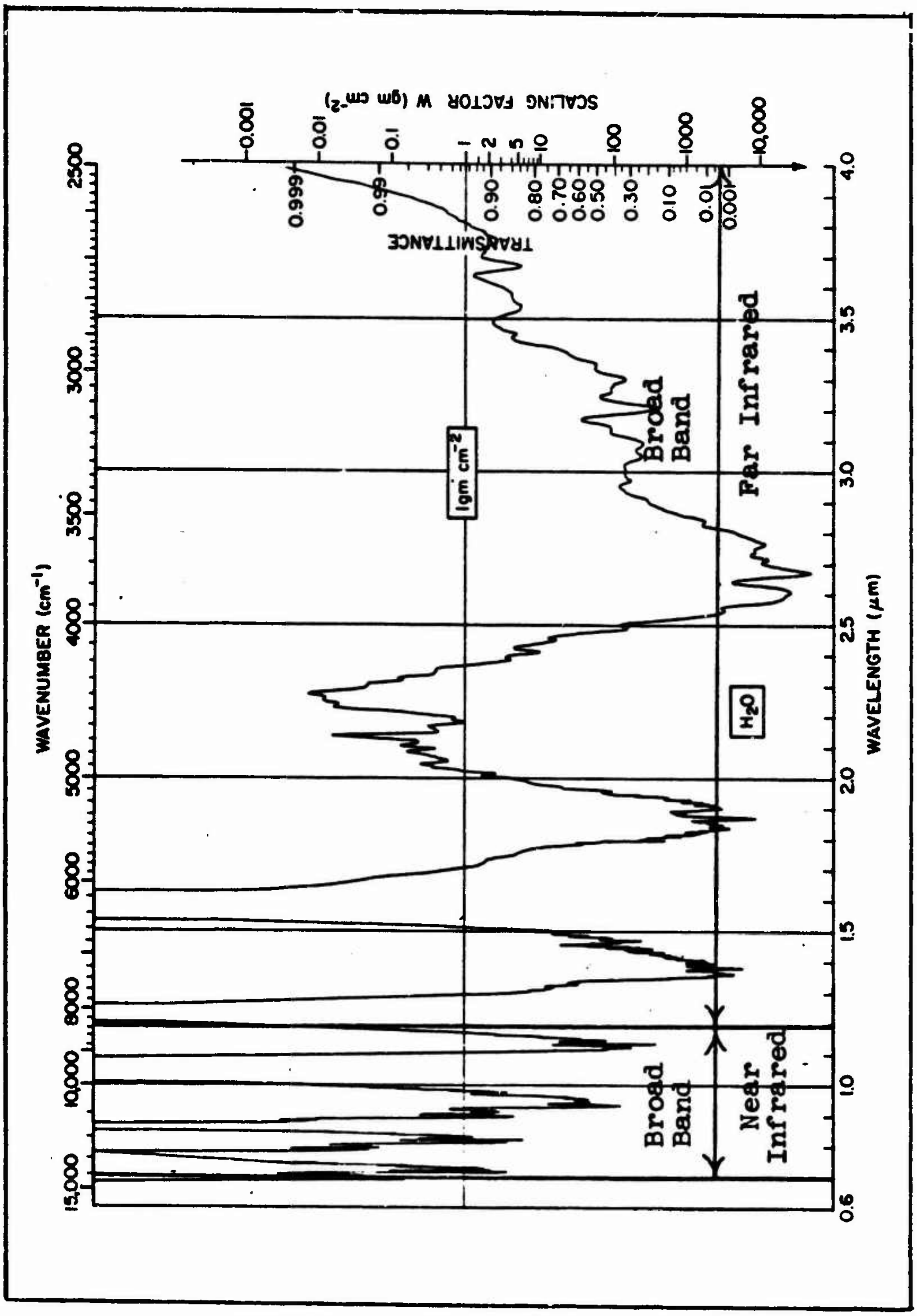

Fig. 5. Prediction Chart for Water Vapor Transmittance (0.6 - 4.0 microns) (Ref 8:59)

to water vapor. The results of the calculated fluence (cal per cm^2) at various horizontal ranges are given in Table III.

The conclusion drawn is that the "fine" band grouping gives consistently larger values for the fluence calculated at various ranges than the "broad" band grouping. At 10-km range the difference is nearly a factor of 8; 2.3 versus 0.3 cal per cm^2. Two cal per cm^2 will ignite shredded newspaper (Ref 6:332).

Importance of Scatter

Many thermal calculations ignor scatter of the thermal radiation (Ref 2, 3 and 7), and treat only the virgin (or unreacted) fluence. Some scatter does occur. The question is, how important is its contribution?

The relative importance is measured here by computing the virgin or direct fluence with two different attenuation cross sections; absorption only and absorption plus scatter. The true answer must be in between the fluences computed with those two cross sections. Absorption only assumes scatter does not occur and is the upper limit. Absorption plus scatter assumes every scatter as removal and the photon can never reach the target point even after multiple scatter, and therefore it is a lower limit. The fluence calculations were made for a 200 kiloton burst with the burst altitude at 5 km and the receiver at 0 km. Cross sections were

Table III

Comparison of "Fine" and "Broad" Band

Infrared Fluence Calculations

(Table entries are energy fluence in cal/cm^2)

b \ a	1 km	3 km	5 km	10 km	15 km	20 km
1	38.3	4.2	1.5	0.4	0.2	0.1
2	65.2	7.2	2.6	0.6	0.3	0.1
3	47.9	4.6	1.4	0.2	0.1	0.0
4	40.4	4.5	1.6	0.4	0.2	0.1
5	24.6	1.8	0.0	0.0	0.0	0.0
6	26.0	2.9	1.0	0.3	0.1	0.1
7	17.6	0.3	0.0	0.0	0.0	0.0
8	22.5	2.5	0.9	0.2	0.1	0.1
9	4.2	0.0	0.0	0.0	0.0	0.0
10	18.6	2.0	0.8	0.2	0.1	0.0
11	0.1	0.0	0.0	0.0	0.0	0.0
12	3.3	0.2	0.0	0.0	0.0	0.0
13	2.1	0.2	0.1	0.0	0.0	0.0
14	1.0	0.1	0.4	0.0	0.0	0.0
Fine	312.0	30.4	10.1	2.3	1.0	0.5
I	230.0	16.8	4.0	0.3	0.1	0.0
II	62.0	2.9	0.4	0.0	0.0	0.0
Broad	292.0	19.7	4.4	0.3	0.1	0.0

[a]Distance between burst and receiver (km)
[b]Band numbers

determined from data in Reference 8. The results of these calculations are shown in Table IV. The results of the dual calculation are illustrated in Figure 6.

The conclusion drawn is that scatter is important in computing fluence at heights below five km. While determining cross sections for absorption and scatter, it was noted that aerosol scatter tends to be the dominant interaction in the visible region for altitudes below five km. The concentration of aerosols in the lower atmosphere is reflected in the contribution of scatter in the computation of thermal fluence.

Temperature of Source

The temperature of the source of thermal radiation can be modeled approximately by a 6000°K blackbody. This fireball model assumes the total thermal yield is radiated at this average temperature. Figure 1 on page 3 of Chapter II illustrates the fact that the temperature of the second pulse rises rather rapidly and cools steadily. During the second pulse, the fireball is radiating thermal energy at different temperatures. The temperatures of interest range from 3500°K to 7500°K. John P. Cahill has modeled a nuclear air burst by time weighting the temperatures of the source to account for the different temperatures at which the source radiates thermal energy during the second pulse. Cahill found the source radiated at an effective temperature

Table IV

Fluence with Absorption plus Scatter

and Absorption only Cross Sections

Distance between burst and receiver (km)	Fluence with absorption and scatter (cal/cm^2)	Fluence with absorption only (cal/cm^2)
5	11.66	15.28
10	2.21	3.51
15	.77	1.49
20	.35	.81
25	.18	.51
30	.10	.35

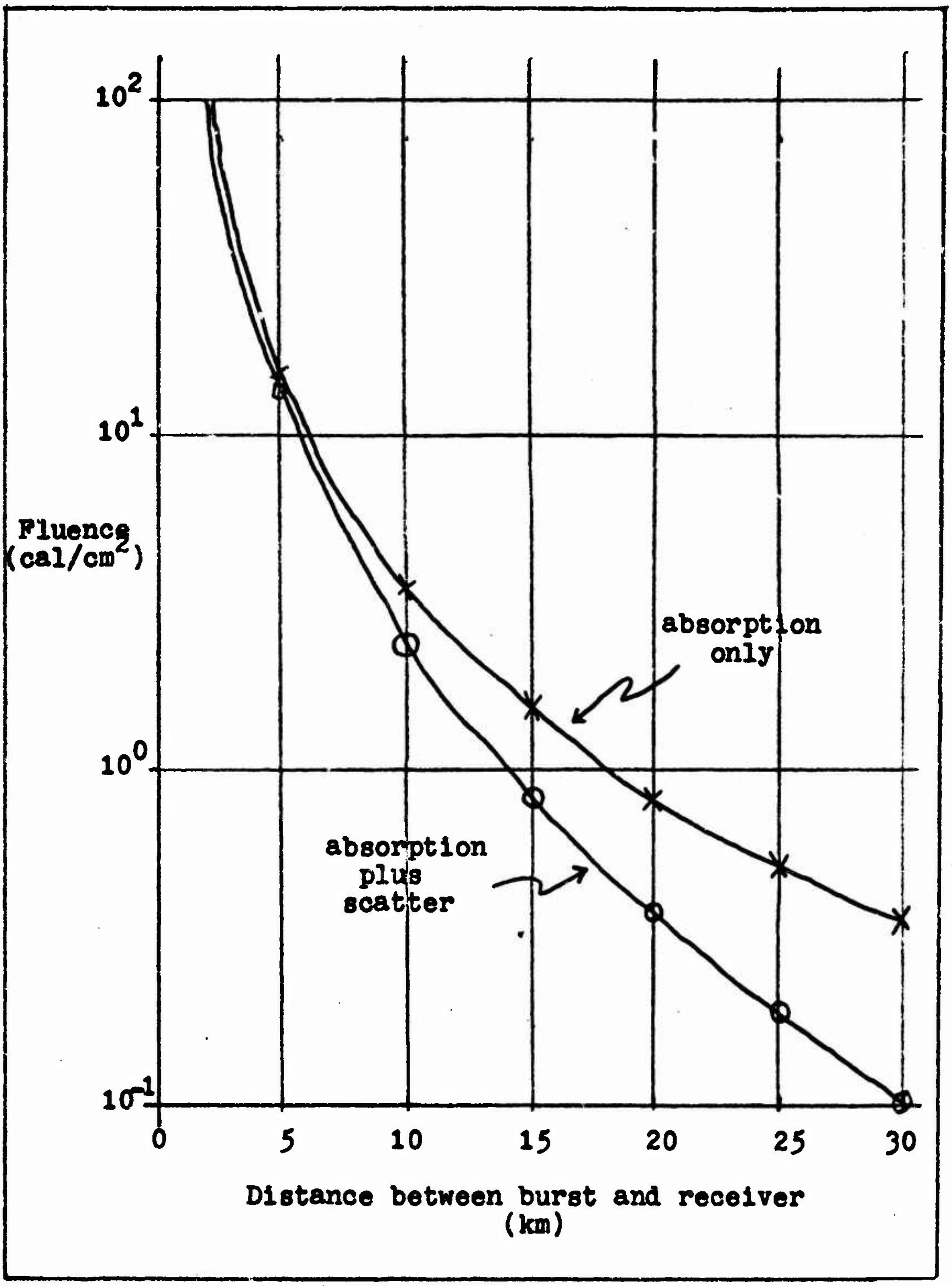

Fig. 6. Fluence with Absorption plus Scatter and Absorption only Cross Sections (Data from Table IV).

of $7500^{\circ}K$ about 43.5% of the time, $6500^{\circ}K$ for 12.5%, $5500^{\circ}K$ for 19.8%, $4500^{\circ}K$ for 14.8% and $3500^{\circ}K$ for 9.4%(Ref 1:17). Using Cahill's weighting factors, the thermal fluence was calculated for a co-altitude burst and receiver of 10 km and a thermal yield of 100 kilotons.

The total virgin fluence calculated at the receiver varied less than five percent between the weighted temperature and the $6000^{\circ}K$ average temperature under the same conditions.

The conclusion is that the computed fluence is relatively insensitive to the source temperature over the energy range considered.

Height of Burst

The thermal fluence from a nuclear air burst is affected by the height of burst. The thermal yield of an air burst is a function of both the height of burst and total weapon yield. For air bursts (less than 30 km), the thermal yield is released during the second thermal pulse. Empirical relationships for the thermal efficiency and thermal yield have been developed by the Analysis Division, Air Force Weapons Laboratory (AFWL), Kirtland AFB, New Mexico. A graph of the thermal efficiency curve developed by AFWL is included in Reference 3. The thermal efficiency, τ, is given by

$$\tau = \exp((-.358 - .009H + 7.14 \times 10^{-4}H^2) \times 2.30) \times \exp((-1.25 \times 10^{-5}H^3 + 6.42 \times 10^{-8}H^4) \times 2.30) \quad (12)$$

where H is the height of burst (km). The thermal yield (kilotons), Y, for an air burst is given by

$$Y = \tau W^{.94} \tag{13}$$

where W is total weapon yield in kilotons. The results for a 200-kiloton total weapon yield are shown in Figure 7.

The percent of photons in the ultraviolet region increases as the burst altitude increases, resulting in an apparent rise in the average surface temperature of the fireball (Ref 7:8). The transmission of thermal radiation is affected by changes in the composition of the atmosphere with changes in altitude. All of these factors, thermal yield, percent of photons in ultraviolet region, and composition of the atmosphere, influence the calculation of fluence from an air burst.

The transmission of thermal radiation is affected by both the height of burst and the height of receiver. In general, the higher the burst and receiver, the fewer the molecules and aerosols available for scatter and absorption. One exception is ozone, which increases to a maximum concentration at approximately 25 km. The effects of water vapor are primarily confined to altitudes less than 10 km. The aerosol distribution varies with the surface visibility only in the lower five km of the atmosphere.

The thermal radiation code, TRAP, developed for AFWL, uses power fractions to represent the distribution of thermal

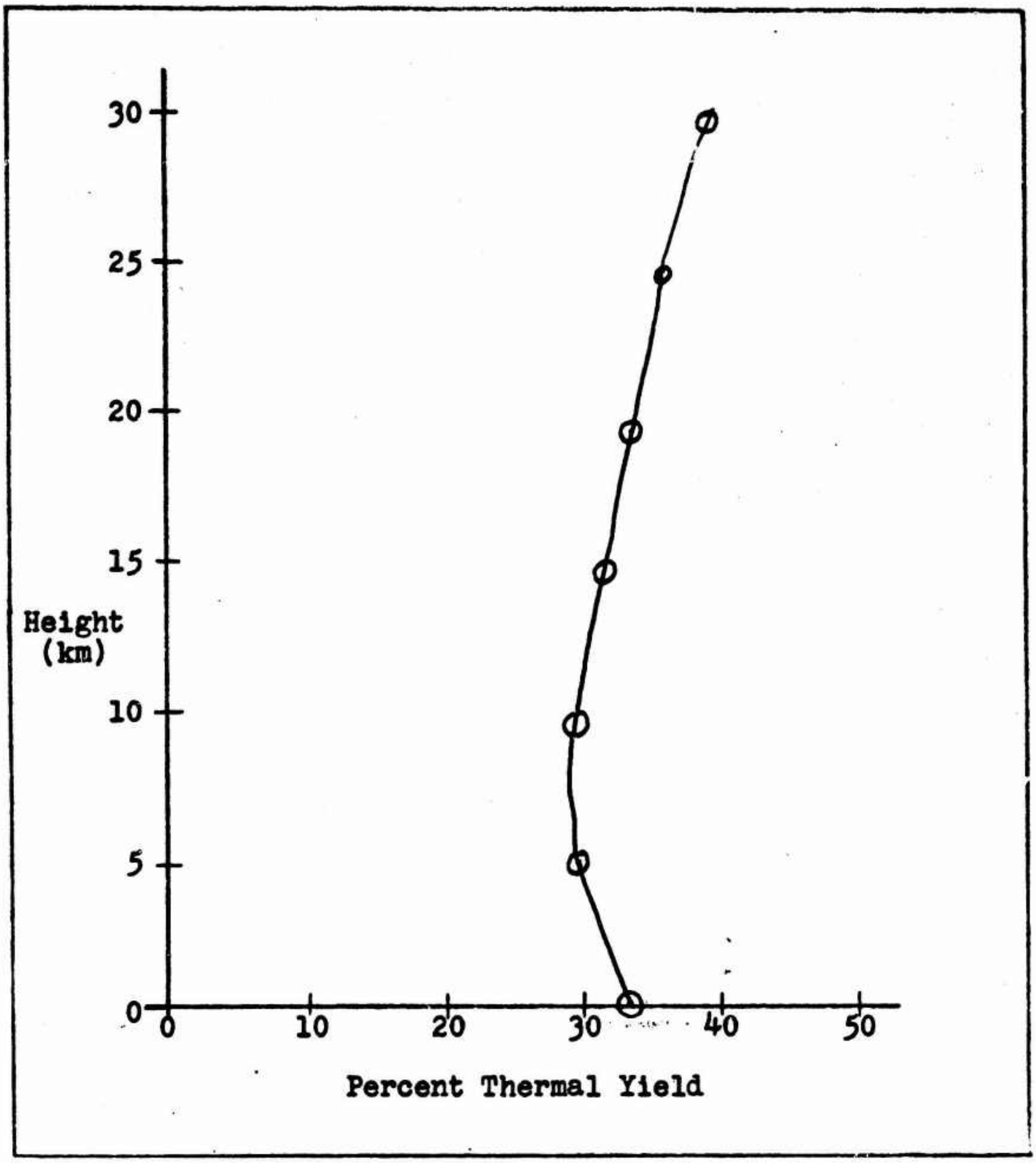

Fig. 7. Percent of Weapon Yield Which is Thermal, Based on a 200-Kiloton Burst Versus Height of Burst in Kilometers.

energy over different bands (Ref 7:8). The power fractions are based on empirical data and distribute the thermal energy approximately like blackbody radiators. The percent of thermal radiation in the ultraviolet region increases with the height of the burst. At 18 km the distribution can be approximated by a 7000°K blackbody and at 32 km by an 8000°K blackbody. Below 15 km, the 6000°K blackbody is a close approximation. The power fractions were compared to blackbody distributions by the use of RAND tables for Planckian distributions (Ref 5). Appendix C illustrates the increase in ultraviolet with height as modeled by the changes in blackbody temperature.

The general decrease in absorption and scatter with height is reflected in the fluence computations in Appendix D for a 200-kiloton burst with distance between burst and receiver of 10 km. The fluence calculated with the height of burst at 5 km in problem one was 2.21 cal per cm^2, and with the height of burst at 20 km in problem four, the fluence was 4.21 cal per cm^2. Part of the increase in fluence is due to increase in thermal yield.

The important conclusion with respect to height of burst is that burst height changes can be modeled by changing source temperature.

V. Virgin Thermal Fluence Code

The findings of the sensitivity studies discussed in Chapter IV and the cross sections determined by methods outlined in Chapter III were used to develop a computer code for calculating the virgin thermal fluence from a nuclear air burst. The code is written in FORTRAN IV computer language. Comment cards are used throughout the program to define terms and identify steps in the calculations. The input parameters are weapon yield in kilotons, height of burst in kilometers, height of receiver in kilometers, distance between burst and receiver in kilometers and surface visibility of 23 or 5 km. The energy distribution fractions and average attenuation cross sections are read into the program at execution time to simplify the program and make the code flexible if different distributions and cross sections are considered.

Thermal Yield

The thermal yield of an air burst is a function of both the height of burst and total weapon yield as mentioned in Chapter IV. Equations (12) and (13), presented in Chapter IV, are used in the code to compute thermal yield.

Attenuation Cross Sections

Average total attenuation cross sections were computed for each of the 16 bands at one-kilometer increments from

0 to 30 km. Bands numbered 1 to 14 were infrared radiation bands. Band number 15 was ultraviolet radiation and band 16 was visible radiation. Cross sections for both the U. S. Standard Atmosphere and the Tropical Atmosphere were determined. Each atmosphere has the lower 5-km cross sections computed for the 23 and 5-km surface visibilities. All cross sections are read into the program on data cards. Calculations are based on whatever atmospheric cross sections are read into the program. The cross sections were determined by methods explained in Chapter III, and they are listed in Appendix B for both the U. S. Standard Atmosphere and the Tropical Atmosphere. All the cross sections were determined based on data found in Reference 8. When the burst and receiver are at different altitudes, the average cross sections for the layer between the height of burst and the height of receiver are calculated for each of the 16 bands.

Distribution of Source Energy

The distribution of source energy is a function of the blackbody temperature used for the fireball model. The $6000^{o}K$ blackbody was used for all burst heights 15 km or less. The $7000^{o}K$ blackbody was the model for a burst at 25 km. For bursts between 15 and 25 km, linear interpolation was used from the $6000^{o}K$ energy distribution to the $7000^{o}K$ energy distribution. For burst heights greater than 25 km, linear interpolation was used from a $7000^{\circ}K$ distribution at 25 km to an $8000^{\circ}K$ distribution at 35 km. The rise in average fireball temperatures was used to model the observed increase in ultraviolet radiation with height. The band divisions are given in Appendix C with the relative distribution of energy for a $6000^{\circ}K$, $7000^{\circ}K$ and $8000^{\circ}K$ Planckian. The distribution of the source thermal energy in terms of ultraviolet, visible and infrared is part of the code output.

Calculation of Fluence

After the thermal yield has been calculated, the energy distribution has been determined and average cross sections for the layer between the burst and receiver heights have been calculated, the virgin fluence contributed by each of the 16 bands is computed. The distance between the burst and receiver is an input parameter used in equation (6) on page 5. Additional factors have been included to convert kilometers to centimeters and kilotons to calories, in order to give the fluence in units of calories per square centimeter. The ultraviolet, visible and infrared virgin fluence computed are separate outputs along with the total virgin fluence.

Options are included to print out the average cross sections computed in the calculation of fluence based on the layer between burst and receiver. The energy distribution computed based on the height of burst is another print-out option. The fluence in each of the 16 bands is also an optional print-out.

Appendix D contains four sample problems illustrating the use of the code in calculating virgin fluence from an air burst. Problems one and two compare the use of the U. S. Standard Atmosphere cross sections with the Tropical Atmosphere cross sections for a surface visibility of 23 km. The difference in the calculated total virgin fluence is due to the difference in the infrared fluence, which is caused by the additional water vapor in the Tropical Atmosphere. Comparing problems two and three, the difference in the total virgin fluence is due to the difference in the visible and infrared fluences caused by the reduction of surface visibility from 23 to 5 km. This illustrates the effect of a haze layer on both the visible and infrared fluences. The haze layer reduced the total virgin fluence more than the difference caused by an increase of water vapor, as shown in the comparison of problems one and two. Problem four demonstrates the increase in total virgin fluence caused by increased thermal yield with increased height of burst and decreased attenuation, due to fewer aerosols and molecules at increased height of burst and receiver. Notice that in all four problems the ultraviolet fluence of contributions is less than one percent of the total virgin fluence.

Appendix A is the program listing for the fluence code.

VI. Results and Recommendations

Results

A sensitivity study was made on four variables used in the calculation of nuclear thermal radiation. The results were:

1. Number and choice of energy bands: Visible and ultraviolet regions could be treated accurately by one band each, but the infrared region needs 14 energy bands to account for atmospheric "windows".
2. Importance of scatter: Scatter is important in computing fluence, particularly at heights below five km.
3. Significance of source temperature: Allowing source emission temperature to vary from 7500°K to 3500°K in five time steps made only a five percent change in fluence as compared to a 6000°K constant temperature source.
4. Importance of height of burst: Increases in source altitude were modeled by increasing blackbody source temperature to 8000°K at 35 km.

A code was developed to calculate virgin thermal fluence from a nuclear air burst. The source of the thermal radiation was considered a blackbody radiator. Cross sections were determined by the use of transmittion data applied to the U. S. Standard Atmosphere and the Tropical Atmosphere compiled by AFCRL. All scatter and absorption interactions were considered loss mechanisms along with attenuation by spherical divergence.

The energy distribution and cross section sensitivities were considered while developing the code. A "fine" band structure was found to be more representative of the infrared range than a "broad" band structure. Increases in the ultraviolet radiation range with increases in height were modeled by increasing the blackbody temperature with height. By changing cross sections, the effects of season, geographical location, and haze layer on the calculated virgin fluence were demonstrated.

The code was written to be easily understood and used with only a basic knowledge of FORTRAN IV language and a brief introduction to thermal nuclear effects. The program was prepared for use on the CDC 6600 computer with a Scope 3.4 compiler version. Core memory required on the CDC system is approximately 40,000 octal words and run times are in the order of a few seconds.

The accuracy of the code calculations for virgin thermal fluence are within the range of the values given by Glasstone. A series of four problems were run using a 200-kiloton burst and a distance between burst and receiver of 10 km. All of the total virgin fluences calculated for surface visibilities of 23 km ranged from two to five calories per cm^2. Glasstone gives a value of approximately three calories per cm^2 for air bursts less than 20 miles with the distance between burst and receiver of 10 km (Ref 6:333). The fluences calculated by the code for bursts less than five km were all less than three cal per cm^2 at a distance of 10 km. The lower fluence values from the code could be attributed to variations in atmospheric models.

The code does not consider reflection from the earth's surface or cloud layers. The only haze layer considered is the ground based haze in the five-km surface visibility model. Attenuation due to rain, snow and clouds was not considered.

Recommendations

Some areas that could be further investigated include the following items. In the future, different cross sections could be determined using other atmospheric models. Since the aerosol model used has the same distribution of aerosols above five km and aerosol cross sections were the largest part of the atmospheric attenuation for a number of calculations, other aerosol models could be tried to illustrate their effects on thermal fluence. The reaction of ultraviolet photons with ozone could be examined. There is a possibility of the photo-decomposition of the ozone in the atmosphere by the initial photons from a burst and the subsequent photons penetrating to the receiver because of the depletion of the absorbing ozone. The photo-decomposition rate and the rate of recombination to ozone equilibrium could be examined.

Bibliography

1. Cahill, J. P. et al. Effective Transmission of Thermal Radiation from Nuclear Detonations in Real Atmosphere. AFCRL-62-456. L. G. Hanscom Field, Bedford, Mass: Air Force Cambridge Research Laboratories, April 1962.

2. Clifton, J. V. Method for Predicting the Amount of Thermal Radiation Incident on a Plane Receiver from a Nuclear Weapon Detonation. General Dynamics Report FZA-333, 31 May 1960.

3. DeRaad, R. G. CSSANE: A Code for System Analysis - Nuclear Effects. Master Thesis. Wright-Patterson Air Force Base, Ohio: Air Force Institute of Technology, 27 July 1972.

4. Electro-Optics Handbook. RCA Defense Electronic Products, P. O. Box 538, Burlington, Mass., October 1974.

5. Gilmore, F. R. A Table of the Planck Radiation Function and its Integral. RM-1743, U. S. Air Force Project RAND, 2 July 1956.

6. Glasstone, S., Ed. The Effects of Nuclear Weapons. Washington, D. C., U. S. Government Printing Office, 1962.

7. Hobbs, N. P., et al. TRAP: A Digital Computer Program for Calculating the Response of Aircraft to the Thermal Radiation From a Nuclear Explosion. AFWL-TR-71-61, Vol. I, Kirtland Air Force Base, New Mexico: Air Force Weapons Laboratory, October 1972.

8. McClatchey, R. A. et al. Optical Properties of the Atmosphere. AFCRL-72-0497. L. G. Hanscom Field, Bedford, Mass: Air Force Cambridge Research Laboratory, 24 August 1972.

9. Sharp, A. L. et al. Spectral Characteristics of Thermal Radiation Predicted From Sputter Calculations. AFWL-TR-73-152. Kirtland Air Force Base, New Mexico: Air Force Weapons Laboratory, August 1973.

Appendix A

Fluence Code Listing

```
C THIS PROGRAM IS FOR CALCULATING VIRGIN FLUENCE IN CAL/CM2
C FOR AIR BURST AND RECEIVER LESS THAN OR EQUAL TO 30 KILOMETERS
C
      PROGRAM FLUENCE (INPUT,OUTPUT)
      DIMENSION F(20),XY(20),U(20),HU(31,16),XU(16),EU(16),XP(8,16)
      INTEGER  H, DH
C XP(J,I) =  FRACTIONS OF THERMAL YIELD IN 16 BANDS
C J = 6,7&8 BASED ON 6000,7000 &8000 KELVIN PLANCKIAN
      DO 1  J = 6, 8, 1
C PLANCKIAN DISTRIBUTIONS READ FROM DATA CARDS
      READ 2, (XP(J,I), I = 1,16)
 1    CONTINUE
 2    FORMAT (7F10.5)
C HU(J,I) = X SECTIONS FOR 16 BANDS AND 0 THROUGH 30 KM HEIGHTS
      DO 3  J = 1,31
C CROSS SECTIONS READ FROM DATA CARDS
      READ 4, (HU(J,I),I= 1,16)
 3    CONTINUE
 4    FORMAT (7F10.5)
C W = WEAPON YIELD IN KILOTONS
C HB = HEIGHT OF BURST IN KILOMETERS
C HR = HEIGHT OF RECEIVER IN KILOMETERS
C R = DISTANCE BETWEEN BURST AND RECEIVER IN KILOMETERS
C V = SURFACE VISIBILITY IN KILOMETERS, 5 OR 23
C W, HB, HR, R AND V READ FROM DATA CARD
      READ 5, W, HB, HR, R,V
 5    FORMAT (5F10.5)
      IF(V.EQ.5.0) GO TO 6
      GO TO 9
 6    DO 7 J = 1,6
      READ 8,(HU(J,I),I=1,16)
 7    CONTINUE
 8    FORMAT (7F10.5)
```

```
C TEFF =   THERMAL EFFICIENCY
 9     TEFF = EXP((-3.5797123E-1-8.804057E-3*HB+7.13680E-4*HB*HB
      1-1.254800E-5*HB*HB*HB+6.423205E-8*HB*HB*HB*HB)*2.302585093)
C Y = THERMAL YIELD AT ALTITUDE , KILOTONS
       Y = TEFF*W**.94
C USE 6000 KELVIN ENERGY DISTRIBUTION FOR HB = OR < 15 KM
       IF (HB.LE.15.0) GO TO 21
C USE 7000 KELVIN ENERGY DISTRIBUTION FOR HB = 25 KM
       IF (HB.EQ.25.0) GO TO 23
C USE INTERPOLATION FOR  15<HB<25
       IF (HB.LE.25.0) GO TO 25
C USE INTERPOLATION FOR HB > 25 KM
C XY(I) = LINEAR INTERPOLATION BETWEEN 7000 AND 8000 KELVIN
       DO 20 I = 1,16
       XY(I) =    ((HB - 25.0)*XP(8,I))/10.0 + ((35.0-HB)/10.0)*XP(7,I)
 20    CONTINUE
       GO TO 27
C XY(I) =    FRACTIONS FOR 6000 KELVIN PLANCKIAN
 21    DO 22 I = 1,16
       XY(I) = XP(6,I)
 22    CONTINUE
       GO TO 27
C XY(I) =    FRACTIONS FOR 7000 KELVIN PLANCKIAN
 23    DO 24 I = 1,16
       XY(I) = XP(7,I)
 24    CONTINUE
       GO TO 27
C XY(I) = LINEAR INTERPOLATION BETWEEN 6000 AND 7000 KELVIN
 25    DO 26 I = 1,16
       XY(I) = ((HB-15.0)*XP(7,I))/10.0 + ((25.0-HB)*XP(6,I))/10.0
 26    CONTINUE
 27    CONTINUE
```

```
C FRACTION OF THERMAL YIELD IN VISIBLE IS XY(16)
C FRACTION OF THERMAL YIELD IN ULTRAVIOLET IS XY(15)
C FIR = FRACTION OF THERMAL YIELD IN IR
      FIR = 0.0
      DO 28  I = 1, 14
      FIR = XY(I) + FIR
 28   CONTINUE
C  YIR = YIELD IN INFRARED
      YIR = FIR*Y
C  YUV = YIELD IN ULTRAVIOLET
      YUV = XY(15)*Y
C  YV = YIELD IN VISIBLE
      YV = XY(16)*Y
      X = HR
      IF(HB-HR) 30,31,31
 30   X = HB
C H = HEIGHT, 1 IS 0KM, 2 IS 1KM, ETC
 31   H = X    + 1.0
C DH = DIFFERENCE BETWEEN HB AND HR
      DH =   ABS(HB-HR)
C CO-ALTITUDE BURST
      IF(DH -1) 35,38,32
C HU = X SECTIONS AT HEIGHT H
C EU = END X SECTIONS
C XU = MIDDLE X SECTIONS
C U = AVERAGE X SECTIONS
 32   XU(1) = 0.0
      DO 34 I = 1,16
      EU(I) = HU(H,I)/2.0 + HU(H+DH,I)/2.0
      J = DH -1
      DO 33 K = 1,J
      XU(I) = HU(H+K,I) + XU(I)
 33   CONTINUE
 34   CONTINUE
```

```
C AVERAGE X SECTIONS
      DO 35 I = 1, 16
      U(I) =(EU(I) + XU(I))/DH
 35   CONTINUE
      GO TO 40
 36   DO 37 I = 1, 16
      U(I) = HU(H,I)
 37   CONTINUE
      GO TO 40
 38   DO 39 I = 1, 16
      U(I) = ( HU(H,I) + HU(H+1,I))/2.0
 39   CONTINUE
C FT = TOTAL FLUENCE, CAL/CM**2
      FT=0.0
 40   DO 41 I = 1, 16
C F(I) = FLUENCE IN GIVEN BAND, CAL/CM**2
      F(I) = ((XY(I)*(Y*(10.0**12.0)))*EXP(-1.0*U(I)*R))/
     A (12.56637*((R*(10.0**5.0))**2.0))
      FT=FT+F(I)
 41   CONTINUE
C XIR = VIRGIN FLUENCE IN IR, TOTAL
      XIR = 0.0
      DO 42 I = 1, 14
      XIR = F(I) + XIR
 42   CONTINUE
C THE 80 SERIES OF PRINT  STATEMENTS IS OPTIONAL
      DO 80 J = 1,31
      PRINT 81,(HU(J,I),I=1,16)
 80   CONTINUE
 81   FORMAT (7F10.5)
      PRINT 82,(XY(I),I = 1,16)
 82   FORMAT ( 1X,7F10.5)
      PRINT 83, (U(I), I = 1,16)
 83   FORMAT ( 1X, 7F10.5)
      PRINT 84, (F(I),I=1,16)
 84   FORMAT ( 1X,7E11.5)
```

```
C THE 90 SERIES PRINT STATEMENTS LIST INPUT AND OUTPUT PARAMETERS
      PRINT 90
   90 FORMAT (1H1,3X,* DATA PAGE * ///)
      PRINT 91
   91 FORMAT ( 3X,* VIRGIN THERMAL FLUENCE PROBLEM  *///
     12X,* INPUT PARAMETERS...*//)
      PRINT 92,W, HB, HR, R,V
   92 FORMAT ( 4X,* WEAPON YIELD IS*,F5.0,* KILOTONS *//
     14X,* HEIGHT OF BURST IS*,F5.0,* KM*//
     24X,* HEIGHT OF RECEIVER IS*,F5.0,* KM*//
     34X,* DISTANCE BETWEEN BURST AND RECEIVER IS*,F5.0,* KM*//
     44X,* PREVAILING SURFACE VISIBILITY IS*,F5.0,* KM*//)
      PRINT 93
   93 FORMAT ( 4X,* CROSS SECTIONS ARE TROPICAL ATMOSPHERE*//)
C CHANGE FORMAT 93 IF DIFFERENT CROSS SECTIONS USED
      PRINT 94
   94 FORMAT ( 2X,* OUTPUT PARAMETERS...*//,3X,* AT THE SOURCE...*//)
      PRINT 95,YIR, YV, YUV,Y
   95 FORMAT ( 4X,* IR THERMAL YIELD IS *,F8.2,* KILOTONS*//
     14X,* VISIBLE THERMAL YIELD IS *,F8.2,* KILOTONS*//
     24X,* UV THERMAL YIELD IS *,F8.2,* KILOTONS*//
     34X, * TOTAL THERMAL YIELD IS*,F8.2,* KILOTONS*//)
      PRINT 96,XIR, F(16), F(15), FT
   96 FORMAT ( 3X,* AT THE RECEIVER...*//
     14X, * IR VIRGIN FLUENCE IS*,F8.2,* CAL/CM2*//
     24X,* VISIBLE VIRGIN FLUENCE IS *,F8.2,* CAL/CM2*//
     34X,* UV VIRGIN FLUENCE IS *,F8.2,* CAL/CM2*//
     44X,* TOTAL VIRGIN FLUENCE IS*,F8.2,* CAL/CM2*)
      STOP
      END
```

Appendix B

Cross Sections Listing

The average total attenuation cross sections (per km) for the 16 bands in the code are listed in three rows for each altitude from 0 through 30 km. The first two rows are the 14 infrared bands. The third row lists band 15, ultraviolet, and band 16, visible. To the right of each three-row listing is the altitude of the cross sections in km. Pages 47 through 49 list the U. S. Standard Atmosphere Cross Sections for a surface visibility of 23 km. Page 50 lists the haze layer cross sections for the U. S. Standard Atmosphere. Pages 51 through 53 list the Tropical Atmosphere cross sections for a surface visibility of 23 km. Page 54 lists the haze layer cross sections for the Tropical Atmosphere. The average total attenuation cross sections were determined by methods outlined in Chapter III with all data used from Reference 8.

0.139	0.117	0.192	0.091	0.304	0.071	0.99	
0.06	1.67	0.0845	5.57	0.4845	0.08	0.0441	0
.7675	.17325						
0.07142	0.0599	0.1064	0.0459	0.17916	0.0359	0.6054	
0.03	1.0282	0.05045	3.70648	0.30365	0.046	0.02657	1
.574	.09797						
0.03108	0.0253	0.054	0.0188	0.10154	0.0148	0.3636	
0.012	0.6238	0.02775	2.40412	0.18655	0.025	0.01459	2
.461	.05158						
0.016	0.01315	0.0244	0.0097	0.04215	0.0077	0.145	
0.006	0.2475	0.0167	1.24795	0.3822	0.0105	0.00966	3
.392	.03419						
0.00754	0.00505	0.0128	0.0042	0.02447	0.0034	0.0856	
0.0024	0.1173	0.01105	0.87691	0.05215	0.0057	0.00661	4
.3476	.0227						
0.00591	0.0047	0.0092	0.00325	0.01633	0.00265	0.0573	
0.0018	0.0984	0.0085	0.64614	0.0365	0.0039	0.00518	5
.32046	.01987						
0.00428	0.00335	0.0056	0.0023	0.00879	0.0019	0.029	
0.0012	0.0435	0.0059	0.41537	0.02085	0.0021	0.00375	6
.3113	.01793						
0.00456	0.00315	0.0039	0.00225	0.00428	0.00185	0.0106	
0.0012	0.0173	0.00483	0.27714	0.01103	0.0011	0.00317	7
.33168	.01584						
0.00384	0.00303	0.00348	0.0022	0.00334	0.0018	0.0069	
0.0012	0.01036	0.00402	0.21265	0.00808	0.0009	0.00264	8
.35205	.01445						
0.00367	0.00292	0.00314	0.00215	0.00262	0.00175	0.00416	
0.0012	0.00603	0.0032	0.15278	0.00557	0.00075	0.00213	9
.37243	.01327						
0.00351	0.00281	0.00288	0.0021	0.00212	0.0017	0.00232	
0.0012	0.00281	0.00246	0.09751	0.00348	0.00065	0.00161	10
.3928	.01198						
0.0034	0.0027	0.00272	0.00205	0.00192	0.00165	0.00169	
0.0012	0.0017	0.00245	0.09433	0.00318	0.00062	0.00161	11
.52268	.0107						

0.00255	0.00205	0.00206	0.00175	0.00142	0.00125	0.00115	
0.0009	0.00108	0.00191	0.07479	0.00246	0.00046	0.00126	12
.65154	.00901						
0.00255	0.00205	0.00205	0.00175	0.00141	0.00125	0.00108	
0.0009	0.00095	0.00162	0.056	0.00193	0.00045	0.00106	13
.68804	.00901						
0.0024	0.00195	0.00195	0.0015	0.00135	0.0012	0.00106	
0.0009	0.00092	0.0014	0.04212	0.00156	0.00045	0.0009	14
.70842	.00751						
0.0024	0.00195	0.00195	0.0015	0.00135	0.0012	0.00106	
0.0009	0.00092	0.00119	0.0283	0.0012	0.00045	0.00075	15
.78142	.00782						
0.00225	0.00185	0.00185	0.00145	0.0013	0.00115	0.00106	
0.0009	0.00092	0.00111	0.02368	0.00107	0.00045	0.0007	16
.76529	.00643						
0.00225	0.00185	0.00185	0.00145	0.0013	0.00115	0.00106	
0.0009	0.00091	0.00104	0.01906	0.00094	0.00045	0.00065	17
.91129	.00685						
0.00222	0.00183	0.00183	0.00144	0.00129	0.00114	0.00106	
0.0009	0.00091	0.00097	0.01446	0.00082	0.00045	0.0006	18
1.05467	.00678						
0.00154	0.00126	0.00126	0.00098	0.00088	0.00078	0.0007	
0.0006	0.00061	0.00065	0.00964	0.00055	0.0003	0.0004	19
1.19583	.00599						
0.00151	0.00124	0.00124	0.00097	0.00087	0.00077	0.0007	
0.0006	0.00061	0.00063	0.00871	0.00052	0.0003	0.00039	20
1.33861	.00613						
0.00122	0.001	0.001	0.00078	0.0007	0.00062	0.00056	
0.00048	0.00049	0.0005	0.00679	0.00041	0.00024	0.00031	21
1.37147	.00556						
0.0008	0.00065	0.00065	0.0005	0.00045	0.0004	0.00035	
0.0003	0.00031	0.00034	0.00575	0.0003	0.00015	0.00021	22
1.38764	.00485						
0.00064	0.00052	0.00052	0.0004	0.00036	0.00032	0.00028	
0.00024	0.00025	0.00026	0.00386	0.00022	0.00012	0.00016	23
1.32771	.00442						

0.00048	0.00039	0.00039	0.0003	0.00027	0.00024	0.00021	
0.00018	0.00019	0.00019	0.0029	0.00016	0.00009	0.00012	24
1.29129	.00379						
0.00041	0.00033	0.00033	0.00026	0.00023	0.00021	0.00018	
0.00015	0.00016	0.00016	0.00196	0.00013	0.00008	0.00010	25
1.17657	.00337						
0.00034	0.00027	0.00027	0.00021	0.00019	0.00017	0.00014	
0.00012	0.00012	0.00013	0.00193	0.00011	0.00006	0.00008	26
1.16347	.0033						
0.00026	0.00021	0.00021	0.00016	0.00014	0.00013	0.00011	
0.00009	0.00009	0.0001	0.00145	0.00009	0.00005	0.00007	27
1.02875	.00283						
0.00006	0.00004	0.00004	0.00003	0.00003	0.00003	0.00001	
0.00001	0.00001	0.00002	0.00093	0.00002	0.0	0.00001	28
.85086	.00232						
0.00006	0.00004	0.00004	0.00003	0.00003	0.00003	0.00001	
0.00001	0.00001	0.00002	0.00075	0.00002	0.0	0.00001	29
.80786	.00211						
0.00004	0.00003	0.00003	0.00002	0.00002	0.00002	0.00001	
0.0	0.0	0.00001	0.00056	0.00001	0.0	0.00001	30
.73357	.00176						

```
C
C   CROSS SECTIONS FOR VISIBILITY = 5.0 KM
C
.523     .447
.24      1.95     .522     .361      .544     .281     1.2
1.315    .60825   .2345    5.69      .5745    .17      .1341    0
.20142   .1699
.09      1.0882   .2164    .1359     .25916   .1059    .6754
.7765    .24237   .09045   3.74648   .33365   .076     .05657   1
.07008   .0585
.03      .6418    .087     .0458     .12554   .0358    .3846
.54175   .09518   .04275   2.41612   .19555   .034     .02359   2
.027     .02415
.012     .2535    .0354    .0197     .05015   .0147    .152
.41225   .04859   .0217    1.25195   .0852    .0135    .01266   3
.01274   .01045
.0048    .1197    .0172    .0078     .02767   .0062    .0884
.3957    .0285    .01305   .87851    .05335   .0069    .00781   4
.00791   .0058
.0024    .099     .0103    .00415    .01713   .00335   .058
.33148   .02132   .009     .64654    .0368    .0042    .00548   5
```

.1499	.126	.336	0.091	.7054	0.071	2.646	
0.96	4.568	.1205	13.8662	1.2585	.17	.0513	0
.744	.17325						
.0785	.0658	.2008	0.0459	.4423	0.0359	1.691	
0.03	2.923	.07405	9.1451	.81105	.105	.03129	1
.574	.09797						
.0354	.0291	.1116	0.0188	.2621	0.0148	1.026	
0.012	1.783	.04215	5.7226	.49615	.061	.01747	2
.461	.05168						
.01882	.0155	.062	0.0097	.14596	0.0077	.5774	
0.006	1.0042	.0261	3.41418	.2843	.034	.01154	3
.392	.03413						
.00886	.00715	.0304	0.0042	.07293	0.0034	.288	
0.0024	.5015	.01545	1.89089	.14675	.0167	.00749	4
.3476	.0227						
.00627	.005	.014	0.00325	.02971	0.00265	.1125	
0.0018	.195	.0097	.92268	.0623	.0069	.00542	5
.32946	.01987						
.00446	.0035	.008	0.0023	.01548	0.0019	.0566	
0.0012	.0978	.0065	.55364	.03375	.0036	.00387	6
.3113	.01703						
.0043	.00335	.0071	0.00225	.0132	0.00185	.0474	
0.0012	00817	.00563	.4615	.02823	.0031	.00333	7
.29918	.01963						
.00392	.0031	.0046	0.0022	.00646	0.0018	.0198	
0.0012	.0334	.0043	.27718	.0141	.0016	.0027	8
.27905	.01424						
.0037	.00234	.00354	0.00215	.00373	0.00175	.00876	
0.0012	.01408	.00334	.17582	.00556	.001	.00215	9
.26293	.01285						
.00351	.00281	.00296	0.0021	000235	0.0017	.00324	
0.0012	000442	.00249	.10212	.00391	.0007	.00162	10
.2468	.01146						
0.0034	0.0027	.00274	0.00205	000195	0.00165	.00182	
0.0012	.00194	.00246	.09502	.00325	.00062	0.00161	11
.23068	.01007						

0.00255	0.00205	.00207	0.00175	.001472	0.00125	.00134	
0.0069	.0014	.00192	.08111	.00254	.00047	0.00126	12
.21354	.00796						
0.00255	0.00205	.00206	0.00175	.00142	0.00125	.00112	
0.0009	.00102	0.00162	.05621	.00195	0.00045	0.00106	13
.21354	.00796						
0.0024	0.00195	0.00195	0.0015	.00136	0.0012	.00108	
0.0009	.00095	0.0014	.04219	0.00156	0.00045	0.0009	14
.19742	.00656						
0.0024	0.00195	0.00195	0.0015	0.00135	0.0012	.00106	
0.0009	.00092	0.00119	0.0283	0.0012	0.00045	0.00075	15
.19742	.00656						
0.00225	0.00185	0.00185	0.00145	0.0013	0.00115	.00106	
0.0009	.00092	0.00111	0.02369	0.00107	0.00045	0.0007	16
.16129	.00517						
0.00225	0.00185	0.00185	0.00145	0.0013	0.00115	.00106	
0.0009	.00091	0.00104	0.01906	0.00094	0.00045	0.00065	17
.25429	.00533						
0.00222	0.00183	0.00183	0.00144	0.00129	0.00114	0.00106	
0.0009	.00031	0.00097	0.01446	0.00082	0.00045	0.0006	18
.32407	.00531						
0.00154	0.00126	0.00126	0.00098	0.00088	0.00078	0.00071	
0.0006	.00061	0.00065	0.00964	0.00055	0.0003	0.0004	19
.53683	.00473						
0.00151	0.00124	0.00124	0.00097	0.00087	0.00077	0.0007	
0.0006	.00061	0.00063	0.00871	0.00052	0.0003	0.00039	20
.68161	.00466						
0.00122	0.001	0.001	0.00078	0.0007	0.00062	0.00056	21
0.00048	0.00049	0.0005	0.00679	0.00041	0.00024	0.00031	
.89697	.00472						
0.0008	0.00065	0.00065	0.0005	0.00045	0.0004	0.00035	
0.0003	0.00031	0.00034	0.00575	0.0003	0.00015	0.00021	22
.96614	.00401						
0.00064	0.00052	0.00052	0.0004	0.00036	0.00032	0.00028	
0.00024	0.00025	0.00026	0.00386	0.00022	0.00012	0.00016	23
1.10871	.004						

0.00048	0.00039	0.00039	0.0003	0.00027	0.00024	0.00021	
0.00018	0.00319	0.00019	0.0029	0.00016	0.00009	0.00012	24
1.17829	.00356						
0.00041	0.00033	0.00033	0.00026	0.00023	0.00021	0.00018	
0.00015	0.00016	0.00016	0.00196	0.00013	0.00008	0.00010	25
1.17657	.00337						
0.00034	0.00027	0.00027	0.00021	0.00019	0.00017	0.00014	
0.00012	0.00013	0.00013	0.00193	0.00011	0.00006	0.00008	26
1.10347	.0033						
0.00026	0.00021	0.00021	0.00016	0.00014	0.00013	0.00011	
0.00009	.0001	0.0001	0.00145	0.00009	0.00005	0.00007	27
1.02875	.00288						
0.00006	0.00004	0.00004	0.00003	0.00003	0.00003	0.00001	
0.00001	0.00002	0.00002	0.00093	0.00002	0.0	0.00001	28
.95380	.00232						
0.00006	0.00004	0.00004	0.00003	0.00003	0.00003	0.00001	
0.00001	0.00001	0.00002	0.00075	0.00002	0.0	0.00001	29
.88086	.00232						
0.00004	0.00003	0.00003	0.00002	0.00002	0.00002	0.00001	
0.0	0.0	0.00001	0.00056	0.00001	0.0	0.00001	30
.80657	.00197						

```
C
C  CROSS SECTIONS FOR VISIBILITY = 5.0 KM
C
.5399      .456       .666       .361       .9454      .281       2.856
.24        4.748      .2705      13.9862    1.3485     .26        .1413     0
1.3515     .60825
.2285      .1758      .3108      .1359      .5223      .1059      1.761
.09        2.988      .12405     9.1851     .84105     .135       .06129    1
.7765      .24297
.0744      .0621      .1446      .0458      .2861      .0358      1.047
.03        1.801      .05715     5.7346     .50515     .07        .02647    2
.54175     .09518
.03182     .0265      .073       .0187      .15396     .0147      .5844
.012       1.0102     .0311      3.41818    .2873      .037       .01454    3
.41225     .04869
.01406     .01155     .0348      .0078      .07613     .0062      .2908
.0348      .5039      .01745     1.89249    .14795     .0179      .00869    4
.3557      .0285
.03627     .0961      .0151      .00415     .03051     .00335     .1132
.0024      .1956      .0102      .92308     .0626      .0072      .00572    5
.33148     .02132
```

Appendix C

Table V

Planckian Distributions of Energy by Bands and Blackbody Temperature

(Table entries are percent of thermal energy in each band)

Band Numbers	Band Limits (microns)	6000°K (%)	7000°K (%)	8000°K (%)
15	0.2 - 0.4	13.8	22.7	29.8
16	0.4 - 0.7	37.5	39.2	38.3
1	0.7 - 0.75	4.9	4.4	3.7
2	0.75- 0.85	8.3	6.9	5.8
3	0.85- 0.95	6.5	4.5	4.4
4	0.95- 1.05	5.1	4.8	3.2
5	1.05- 1.15	3.9	3.1	2.4
6	1.15- 1.25	3.3	2.6	1.8
7	1.25- 1.50	5.6	4.0	3.1
8	1.50- 1.70	2.9	2.0	1.5
9	1.70- 2.00	2.7	1.9	1.4
10	2.00- 2.50	2.4	1.7	1.2
11	2.50- 3.00	1.2	0.8	0.6
12	3.00- 3.50	0.6	0.5	0.3
13	3.50- 3.80	0.3	0.2	0.1
14	3.80- 4.00	0.1	0.1	0.1
Total	0.2 - 4.00	99.1	99.4	97.7

Appendix D

Sample Problems

VIRGIN THERMAL FLUENCE PROBLEM 1

INPUT PARAMETERS...

WEAPON YIELD IS 200. KILOTONS

HEIGHT OF BURST IS 5. KM

HEIGHT OF RECEIVER IS 0. KM

DISTANCE BETWEEN BURST AND RECEIVER IS 10. KM

PREVAILING SURFACE VISIBILITY IS 23. KM

CROSS SECTIONS ARE U.S. STANDARD ATMOSPHERE

OUTPUT PARAMETERS...

AT THE SOURCE...

IR THERMAL YIELD IS 28.52 KILOTONS

VISIBLE THERMAL YIELD IS 22.47 KILOTONS

UV THERMAL YIELD IS 8.25 KILOTONS

TOTAL THERMAL YIELD IS 59.88 KILOTONS

AT THE RECEIVER...

IR VIRGIN FLUENCE IS 1.22 CAL/CM2

VISIBLE VIRGIN FLUENCE IS .96 CAL/CM2

UV VIRGIN FLUENCE IS .01 CAL/CM2

TOTAL VIRGIN FLUENCE IS 2.21 CAL/CM2

VIRGIN THERMAL FLUENCE PROBLEM 2

INPUT PARAMETERS...

WEAPON YIELD IS 200. KILOTONS

HEIGHT OF BURST IS 5. KM

HEIGHT OF RECEIVER IS 0. KM

DISTANCE BETWEEN BURST AND RECEIVER IS 10. KM

PREVAILING SURFACE VISIBILITY IS 23. KM

CROSS SECTIONS ARE TROPICAL ATMOSPHERE

OUTPUT PARAMETERS...

AT THE SOURCE...

IR THERMAL YIELD IS 28.52 KILOTONS

VISIBLE THERMAL YIELD IS 22.47 KILOTONS

UV THERMAL YIELD IS 8.25 KILOTONS

TOTAL THERMAL YIELD IS 59.88 KILOTONS

AT THE RECEIVER...

IR VIRGIN FLUENCE IS 1.05 CAL/CM2

VISIBLE VIRGIN FLUENCE IS .98 CAL/CM2

UV VIRGIN FLUENCE IS .01 CAL/CM2

TOTAL VIRGIN FLUENCE IS 2.03 CAL/CM2

VIRGIN THERMAL FLUENCE PROBLEM 3

INPUT PARAMETERS...

WEAPON YIELD IS 200. KILOTONS

HEIGHT OF BURST IS 5. KM

HEIGHT OF RECEIVER IS 0. KM

DISTANCE BETWEEN BURST AND RECEIVER IS 10. KM

PREVAILING SURFACE VISIBILITY IS 5. KM

CROSS SECTIONS ARE U.S. STANDARD ATMOSPHERE

OUTPUT PARAMETERS...

AT THE SOURCE...

IR THERMAL YIELD IS 28.52 KILOTONS

VISIBLE THERMAL YIELD IS 22.47 KILOTONS

UV THERMAL YIELD IS 8.25 KILOTONS

TOTAL THERMAL YIELD IS 59.88 KILOTONS

AT THE RECEIVER...

IR VIRGIN FLUENCE IS .72 CAL/CM2

VISIBLE VIRGIN FLUENCE IS .42 CAL/CM2

UV VIRGIN FLUENCE IS .00 CAL/CM2

TOTAL VIRGIN FLUENCE IS 1.13 CAL/CM2

VIRGIN THERMAL FLUENCE PROBLEM 4

INPUT PARAMETERS...

WEAPON YIELD IS 200. KILOTONS

HEIGHT OF BURST IS 20. KM

HEIGHT OF RECEIVER IS 30. KM

DISTANCE BETWEEN BURST AND RECEIVER IS 10. KM

PREVAILING SURFACE VISIBILITY IS 5. KM

CROSS SECTIONS ARE U.S. STANDARD ATMOSPHERE

OUTPUT PARAMETERS...

AT THE SOURCE...

IR THERMAL YIELD IS 28.38 KILOTONS

VISIBLE THERMAL YIELD IS 25.61 KILOTONS

UV THERMAL YIELD IS 12.17 KILOTONS

TOTAL THERMAL YIELD IS 66.72 KILOTONS

AT THE RECEIVER...

IR VIRGIN FLUENCE IS 2.25 CAL/CM2

VISIBLE VIRGIN FLUENCE IS 1.96 CAL/CM2

UV VIRGIN FLUENCE IS .00 CAL/CM2

TOTAL VIRGIN FLUENCE IS 4.21 CAL/CM2

Vita

Joel David Johnson was born [redacted], I[redacted] He received the degree of Bachelor of Science from Northern Illinois University in 1964. He served as a Peace Corps Volunteer in the Republic of the Philippines for two years. On August 21, 1967 he was commissioned through Officer Training School, Lackland AFB, Texas. Assigned to Air Weather Service, he studied Meteorology at Texas A & M University before duty as a weather forecaster at Wheelus AB, Libya. He spent four years as a meteorology instructor at Chanute AFB, Illinois, and is presently enrolled in the Air Force Institute of Technology. He received a commission in the Regular Air Force in August, 1970. He is a member of Chi Epsilon Pi, honorary society for meteorologists, and the American Nuclear Society.

Permanent address: [redacted]

This thesis was typed by Cathleen M. Johnson